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Naval Research Laboratory and
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Research Studies on Short Wavelength Lasers by Selective Auger Processes

Final Technical Report for the period

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I. OVERVIEW

LASER SYSTEM

During this contract period our major effort has been the construction of a first-of-its-kind ultrashort-pulse laser system. We are building this system for two purposes: (1) The generation of short pulse incoherent x-rays, and (2) for experiments on new types of extreme ultraviolet lasers. The system has been constructed primarily under the direction of Prof. Christopher Barty. Although it has taken somewhat longer than planned, we have attained the complete specifications which were sought: An energy of 135 mJ, a pulselength of 35 fs, and near diffraction limited beam quality with a 10 Hz repetition rate. This is the first such system ever made which produces sub-50-fs pulses with terawatt peak power. It is one of the brightest laser sources in existence, regardless of pulse duration or energy. It is also the first system to control femtosecond-time-scale phase and amplitude distortions during terawatt level amplification.

INCOHERENT X-RAY GENERATION

The first application of this laser source will be in time-gated x-ray imaging. The key idea is to overcome x-ray scattering. Scattered x-ray photons which reach the detector decrease the contrast and increase the noise of the image. Typically, for every photon traversing 20 cm of human tissue with 2 cm of bone density material in the path, there will be seven scattering events. Our plan is to use the x-rays from our laser-driven source, together with a time-gated detector, to overcome the effects of the scattered photons.

If one uses a detector which may be turned off rapidly after the arrival of the ballistic photons, then the scattered photons may be removed from the image. Calculations show that it should be possible to obtain a reduction of x-ray dosage of 7.7.

FEMTOSECOND-PULSE-DRIVEN XUV LASERS

Intense femtosecond-time-scale pulses may allow the construction of unusually simple and, possibly, practical extreme ultraviolet lasers. In recent work we have calculated and suggested the use of photoionization to prepare a target species and to produce hot electrons which inelastically excite the target species. A laser at 10^{16} W/cm^2 should strip the outer shell of the target species by tunneling ionization and should produce electrons with sufficient energy to collisionally excite the upper laser level. Theory predicts that electrons which are produced via tunneling ionization with circularly polarized light will retain a kinetic energy equal to the instantaneous quiver energy which corresponds to the instantaneous electric field at the time at which the electron is ionized. We have recently modeled three systems: Xe IX, Ar IX, and Kr IX. These systems should lase at 41 nm, 48 nm, and 32 nm, respectively. After the completion of this contract period the experiments referred to above were performed and the first operation of this laser has been demonstrated.

Portions of the work reported here were jointly supported by the Air Force Office of Scientific Research, the Army Research Office, and the Office of Naval Research.

II. I [illegible] OF PUBLICATIONS

1. K.-J. Boller, A. Imamoglu, and S. E. Harris, "Observation of Electromagnetically Induced Transparency," *Phys. Rev. Lett.* **66**, 2593-2596 (May 1991).

2. M. H. Sher and S. J. Benerofe, "Prepulsing of Laser-Produced Plasmas for More Efficient Pumping of Extreme-Ultraviolet Lasers," *J. Opt. Soc. Am. B* **8**, 2437-2441 (December 1991).

3. K.-J. Boller, A. Imamoglu, and S. E. Harris, "Electromagnetically Induced Transparency in Sr Vapor," in *Laser Spectroscopy*, edited by M. Ducloy, E. Giacobino, and G. Camy (New Jersey, World Scientific, 1992), pp. 295-300.

4. J. D. Kmetec, C. L. Gordon III, J. J. Macklin, B. E. Lemoff, G. S. Brown, and S. E. Harris, "MeV X-Ray Generation With a Femtosecond Laser," *Phys. Rev. Lett.* **68**, 1527-1530 (March 1992).

5. C. P. J. Barty, G. Y. Yin, J. E. Field, D. A. King, K. H. Hahn, J. F. Young, and S. E. Harris, "Studies of a 96.9-nm Laser in Neutral Cesium," *Phys. Rev. A* **46**, 4286-4296 (October 1992).

6. B. E. Lemoff and C. P. J. Barty, "Generation of High Peak Power 20 fs Pulses from a Regeneratively Initiated, Self-Mode-Locked Ti:Sapphire Laser," *Opt. Lett.* **17**, 1357-1369 (October 1992).

7. S. J. Benerofe, G. Y. Yin, and S. E. Harris, "116 nm H_2 Laser Pumped by a Traveling-Wave Photoionization Electron Source," in *Vacuum Ultraviolet Radiation Physics*, edited by F. J. Wuilleumier, Y. Petroff, and I. Nenner (New Jersey, World Scientific, 1993), pp. 85-95.

8. C. P. J. Barty, C. L. Gordon III, J. D. Kmetec, B. E. Lemoff, and S. E. Harris, "Ultrashort High Peak Power Lasers and Generation of Hard Incoherent X-Rays," in *Proceedings of of the International Conference on Lasers '92*, edited by C. P. Wang (McLean, VA, STS Press, 1993), pp. 44-51.

9. C. P. J. Barty, B. E. Lemoff, and C. L. Gordon III, "Generation, Measurement, and Amplification of 20-fs High-Peak-Power Pulses from a Regeneratively Initiated Self-Mode-Locked Ti:Sapphire Laser," in *SPIE Proceedings on Ultrafast Pulse Generation and Spectroscopy*, (Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1993), 1861, pp. 6-30.

10. B. E. Lemoff, C. L. Gordon III, and C. P. J. Barty, "Design of a Quintic-Phase-Limited Amplification System for Production of Multi-Terawatt 20-fs, 800-nm Pulses," in *OSA Proceedings on Shortwavelength V: Physics with Intense Laser Pulses*, edited by Corkum. Paul B. and Michael D. Perry (Washington, DC, Optical Society of America, 1993), pp. 31-35.

11. B. E. Lemoff and C. P. J. Barty, "Cubic-Phase-Free-Dispersion Compensation in Solid-State Ultrashort-Pulse Lasers," *Opt. Lett.* **18**, 57-59 (January 1993).

12. J. J. Macklin, J. D. Kmetec, and C. L. Gordon III, "High-Order Harmonic Generation Using Intense Femtosecond Pulses," *Phys. Rev. Lett.* **70**, 766-769 (February 1993).

13. S. E. Harris, "Electromagnetically Induced Transparency with Matched Pulses," *Phys. Rev. Lett.* **70**, 552-555 (February 1993).

14. S. E. Harris, J. J. Macklin, and T. W. Hänsch, "Atomic Scale Temporal Structure Inherent to High-Order Harmonic Generation," *Opt. Commun.* **100**, 487-490 (July 1993).

15. J. E. Field and A. Imamoglu, "Spontaneous Emission Into an Electromagnetically Induced Transparency," *Phys. Rev. A* **48**, 2486-2489 (September 1993).

16. B. E. Lemoff and C. P. J. Barty, "Quintic-Phase-Limited, Spatially Uniform Expansion and Recompression of Ultrashort Optical Pulses," *Opt. Lett.* **18**, 1651-1653 (October 1993).

17. C. P. J. Barty, B. E. Lemoff, C. K. Gordon III, and P. T. Epp, "Multiterawatt Amplification of Ultrabroadband Optical Pulses: Breaking the 100 fs Limit," in *SPIE Proceedings on Generation, Amplification, and Measurement of Ultrashort Laser Pulses*, edited by Rick P. Trebino and s;eu. Oam A/ Wa; (Bellingham, WA, SPIE - The International Society for Optical Engineering, 1994), 2116, pp. 184-194.

18. B. E. Lemoff, C. P. J. Barty, and S. E. Harris, "Femtosecond-Pulse-Driven, Electron-Excited XUV Lasers in Eight-Times-Ionized Noble Gases," *Opt. Lett.* **19**, 569-571 (April 1994).

19. C. P. J. Barty, C. L. Gordon III, B. E. Lemoff, P. T. Epp, and S. E. Harris, "Ultrashort Pulse Terawatt Lasers for the Generation of Coherent and Incoherent X-Ray Sources," in *Proceedings of Lasers '93* (to be published).

20. B. E. Lemoff, G. Y. Yin, C. L. Gordon III, C. P. J. Barty, and S. E. Harris, "Demonstration of a 10-Hz, Femtosecond-Pulse-Driven XUV Laser at 41.8 nm in Xe IX," *Phys. Rev. Lett.* (submitted for publication).

APPENDIX A

ABSTRACTS OF PUBLISHED WORK

Observation of Electromagnetically Induced Transparency

K.-J. Boller, A. Imamoğlu, and S. E. Harris

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(Received 12 December 1990)

We report the first demonstration of a technique by which an optically thick medium may be rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmittance of an autoionizing (ultraviolet) transition in Sr is changed from $\exp(-20)$ without a coupling laser present to $\exp(-1)$ in the presence of a coupling laser.

Prepulsing of laser-produced plasmas for more efficient pumping of extreme-ultraviolet lasers

M. H. Sher and S. J. Benerofe

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Received January 29, 1990

We have used a low-energy prepulse to enhance the soft-x-ray emission of laser-produced plasmas in a parameter range that has been used to pump photoionization lasers. We have prepulsed a laser-produced-plasma-pumped Xe III 109-nm laser, which was pumped with an 80-ps 1064-nm pulse, and we observed a greater than tenfold increase in output.

MeV X-Ray Generation with a Femtosecond Laser

J. D. Kmetec, C. L. Gordon, III, J. J. Macklin, B. E. Lemoff, G. S. Brown,[a] and S. E. Harris

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305

(Received 17 December 1991)

A 0.5-TW, 120-fs Ti:sapphire laser, when focused to greater than 10^{17} W/cm^2 onto a solid target, creates a *plasma which emits* radiation that extends beyond 1 MeV. The x-ray yield increases as the $\frac{3}{2}$ power of the incident laser energy, reaching 0.3% energy conversion to radiation above 20 keV at 40 mJ of laser energy on target. An x-ray spectral distribution of $1/E$ fits the data for most of the radiation, falling faster at higher photon energies.

ELECTROMAGNETICALLY INDUCED TRANSPARENCY IN SR VAPOR

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Abstract

We report the first demonstration of a technique by which an optically thick medium may be rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmittance of an autoionizing (ultraviolet) transition in Sr is increased from exp(-20) without a coupling laser present to exp(-1) in the presence of a coupling laser.

Studies of a 96.9-nm laser in neutral cesium

C. P. J. Barty, G. Y. Yin, J. E. Field, D. A. King, K. H. Hahn, J. F. Young, and S. E. Harris
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(Received 4 May 1992)

Investigations of a 96.9-nm laser in neutral cesium are described. Theoretical and experimental evidence is presented for the laser level designation and pumping mechanism. Measurements of the laser output are given, including saturated pulse energy, temporal profile, spatial profile, transition wavelength, gain cross section, and the variation of small signal gain with operating parameters. Comparisons of the temporal and spatial behavior of the 96.9-nm laser emission with respect to resonance line emission from ionic Cs are also presented.

Generation of high-peak-power 20-fs pulses from a regeneratively initiated, self-mode-locked Ti:sapphire laser

B. E. Lemoff and C. P. J. Barty

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Received June 15, 1992

We report the generation and measurement of 804-nm pulses with durations as short as 20 fs and with peak powers as high as 500 kW from a regeneratively initiated, self-mode-locked Ti:sapphire laser. Pulse duration is shown to decrease, and spectral content to increase, as intracavity power is increased. Control of intracavity focusing and a high-modulation-depth, acousto-optic modulator allow the intracavity power to be maximized. Cavity cubic phase error is minimized by correct design and placement of a group-velocity-dispersion-compensating prism pair.

116 nm H_2 Laser Pumped by a Traveling-Wave Photoionization Electron Source

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We discuss the use of a photoionization electron source (PES) to pump a 116 nm laser in the Werner band ($C^1\Pi_u$ -> $X^1\Sigma_g^+$) of molecular hydrogen. The laser is pumped by free electrons which are created by photoionizing molecular hydrogen with soft x-rays from a traveling-wave laser plasma. The pumping configuration presented has allowed 2 Hz operation and saturation of the 116 nm Werner band laser. Using PES pumping we have measured a small signal gain coefficient of 1.6 cm^{-1}, an improvement of more than a factor of 10 over previously reported e-beam and discharge pumped results. We also report results showing that the small signal gain coefficient can be increased by cooling the laser medium, thereby reducing the Doppler width of the laser transition. We show that even though the free electrons have an average temperature of ~10 eV, the lasing hydrogen molecules retain an ambient temperature of < 0.02 eV. We measure an extrapolated small signal gain of exp(43), with a 1064 nm pump energy of 580 mJ in 200 psec.

ULTRASHORT HIGH PEAK POWER LASERS AND GENERATION OF HARD INCOHERENT X-RAYS

C. P. J. Barty, C. L. Gordon III, J. D. Kmetec, B. E. Lemoff and S. E. Harris

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Abstract

The design, construction, and use of high peak power infrared laser pulses for the generation of diagnostic (20 keV to 150 keV) x-rays are discussed. A review of recent laser-plasma generation of diagnostic x-rays is presented. The advantages of such sources include subpicosecond pulse duration and extremely small source size. Because of their short duration, it should be possible to form time-gated medical images with up to eight times less x-ray flux than with conventional x-ray sources. Details of a next generation laser driver are also presented. Generation of 20-fs pulses from a regeneratively initiated, self-mode-locked Ti:sapphire laser is described. Techniques for amplification of these pulses to peak powers of 5 TW are presented.

Generation, measurement, and amplification of 20-fs high-peak-power pulses from a regeneratively initiated self-mode-locked Ti:sapphire laser

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ABSTRACT

We report the generation and measurement of 804 nm pulses with durations as short as 20 fs and with peak powers as high as 500 kW from a regeneratively initiated, self-mode-locked Ti:sapphire laser. Pulse duration is shown to decrease, and spectral content to increase, as intracavity power is increased. Control of intracavity focusing and a high-modulation-depth, acousto-optic modulator allow the intracavity power to be maximized. Cavity cubic phase error is minimized by correct design and placement of a GDD compensating prism pair. Methods for accurate determination of the pulse duration without assumption of pulse shape are discussed. Interferometric autocorrelation is accomplished with an interferometer which intrinsically balances dispersion and loss in each arm. Techniques for eliminating pulse distortions during amplification are also presented.

Design of a Quintic-Phase-Limited Amplification System for Production of Multi-Terawatt 20-fs, 800-nm Pulses

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Abstract

Design of a multi-terawatt amplification system based on reflective optics and capable of supporting sub-20 fs pulses is presented. Tests of a quintic-phase-limited expansion and compression system, which is key to this design, are also discussed.

Cubic-phase-free dispersion compensation in solid-state ultrashort-pulse lasers

B. E. Lemoff and C. P. J. Barty

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Received August 31, 1992

We show that intracavity group-velocity dispersion compensation with the use of prisms composed of conventional optical materials can be accomplished while simultaneously eliminating the round-trip cavity cubic phase. The ability to compensate perfectly both second- and third-order dispersion exists for pulses whose central wavelengths lie within a range that depends on the prism and laser rod materials as well as on the prism angles. In the case of Ti:sapphire and Cr:$LiSrAlF_6$ lasers, Brewster prisms composed of readily available materials can be used to compensate for both group-velocity dispersion and cubic phase over much of the respective tuning ranges.

High-Order Harmonic Generation Using Intense Femtosecond Pulses

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(Received 21 September 1992)

Neon gas excited by 800-nm laser pulses (15 mJ, 125 fsec) at an intensity near 10^{15} W/cm^2 generates harmonics up to the 109th order. The appearance of successively higher harmonics as the laser intensity is increased is compared to recent calculations of the strong-field atomic response. Blueshifting of the laser and harmonic wavelengths indicates a small degree of ionization until the threshold for the highest harmonics ($>$91st) is reached.

Electromagnetically Induced Transparency with Matched Pulses

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(Received 20 August 1992)

We show that electromagnetically induced transparency in a dense media is not a Beer's law superposition of the single atom response. When an arbitrarily shaped pulse is applied to an ensemble of population-trapped atoms, the atoms will generate a matching pulse shape on the complementary transition and, after a characteristic distance, render themselves transparent.

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North-Holland

OPTICS
COMMUNICATIONS

Atomic scale temporal structure inherent to high-order harmonic generation

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Received 20 January 1993

Using intense lasers, several laboratories have generated high-order harmonic spectra which are flat over 20 eV. If the harmonics are appropriately phased, this bandwidth corresponds to temporal pulses on the order of $\sim 5\times10^{-17}$ s, and thereby motivates a search for a new regime of short-pulse generation.

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Spontaneous emission into an electromagnetically induced transparency

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(Received 22 August 1991; revised manuscript received 15 June 1992)

We investigate spontaneous emission into an electromagnetically produced transparency of the form recently proposed [A. Imamoğlu and S. E. Harris, Opt. Lett. 14, 1344 (1989)]. We show that the achievable radiation temperature (or brightness) at the transparency is much greater than the atomic temperature.

Quintic-phase-limited, spatially uniform expansion and recompression of ultrashort optical pulses

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Received April 15, 1993

gn of an expansion and recompression system for amplification of sub-20-fs optical pulses to multiterawatt ak powers is presented. The system allows one to eliminate spatial inhomogeneities and cubic and quartic ase errors that make existing designs unsuitable for use with pulses much shorter than 100 fs. We xperimentally demonstrate >10,000 times expansion and recompression of ~25-fs optical pulses.

Invited Paper

Multiterawatt Amplification of Ultrabroadband Optical Pulses: Breaking the 100 fs Limit

C. P. J. Barty, B. E. Lemoff, C. L. Gordon III and P.T. Epp

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ABSTRACT

A first of its kind, multiterawatt, ultrashort pulse laser system is described. The system is capable of producing 125-mJ, 35-fs, 800-nm pulses with near diffraction limited beam quality at a 10 Hz repetition rate. Methods for control of phase and amplitude distortion during sub-100-fs amplification are presented.

Femtosecond-pulse-driven, electron-excited XUV lasers in eight-times-ionized noble gases

B. E. Lemoff, C. P. J. Barty, and S. E. Harris

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Received November 22, 1993

We propose three XUV laser schemes in the 30–50-nm wavelength region that can be driven by 10-Hz ultrashort-pulse terawatt laser systems. Tunneling ionization by circularly polarized radiation produces both the ions and hot electrons necessary to excite the upper laser level.

ULTRASHORT PULSE TERAWATT LASERS FOR THE GENERATION OF COHERENT AND INCOHERENT X-RAY SOURCES

C. P. J. Barty, C. L. Gordon III, B. E. Lemoff, P. T. Epp and S. E. Harris

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Abstract

The construction of a new class of terawatt laser systems which operate with pulse durations of ~30 fs is described. Planned experiments with this system to generate sub-picosecond diagnostic x-rays and to generate coherent sources in the 10 nm to 100 nm range are discussed.

Demonstration of a 10-Hz, femtosecond-pulse-driven XUV laser at 41.8 nm in Xe IX

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ABSTRACT

We report the observation of a gain of approximately exp(11) at 41.8 nm in eight-times-ionized xenon. This XUV laser is driven by a 10-Hz, 70-mJ circularly-polarized femtosecond laser pulse. The laser is focused into Xe at pressures ranging from 5 to 12 torr. The laser is collisionally excited, with both the ions and electrons produced by field-induced tunneling.